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**SOUND FIELD DIFFUSIVITY IN NASA LANGLEY
RESEARCH CENTER HARDWALLED ACOUSTIC
FACILITIES**

FOR REFERENCE

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INTRODUCTION

One of the most common ways to characterize sound absorption and sound transmission in structures is through the use of sound power techniques (i.e. energy methods) in reverberation chambers. Sound power methods allow one to reduce an acoustic emission, absorption, or transmission problem to an equivalent electrical circuit problem with a power source and a network of complex impedances (impedances with resistive and reactive components).

In order to use power flow methods in a reverberation chamber, a diffuse sound field is a necessary condition. Schroeder¹ defines diffusion of a sound field at a point as "the angular distribution of sound energy flux in the plane wave expansion of the sound field at that point. If the distribution over the solid angle is uniform, we shall call the sound field at this point completely diffuse." Rewording this, one might say that complete diffusion of the sound field at a point occurs when the time averaged acoustic intensity vector at that point is uniform in all directions.

A substantial amount of research has been devoted to the study of sound-field diffusivity in reverberation rooms [see refs. 1-9]. Many different approaches to the problem have been investigated. The earlier studies [see refs. 2, 3] were primarily analytical attempts to describe room character since measurement equipment was primitive and computers were unavailable. Bolt^{2,3} took a statistical approach to the problem and tried to link the sound-field diffusivity to the "Frequency Irregularity" of the natural frequencies of the room. Later papers by Schroeder^{1,5}, Doak⁴ and others showed that the frequency irregularity is not related to the sound diffusivity

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in large rooms. The experimental portion of Schroeder's papers^{1,5} concentrated on methods for measuring sound-field diffusivity at the wall surfaces of a room. A paper by Sepmeyer⁶ used numerical schemes to show that there exists no truly "optimum" dimensions for a rectangular reverberation room. Doak⁷ provides a summary of the various theories dealing with the topic of room character. Some of the important conclusions reached in the various papers¹⁻⁹ are:

- (1) The randomness of the acoustic field in a rectangular room with smooth hard walls peaks at a particular frequency, and then decreases with increasing frequency [see refs. 3, 4, 7].
- (2) Above a certain critical frequency the statistical parameters of frequency response curves for all rooms are either identical or depend at most on reverberation time [see refs. 4, 5].
- (3) Averaging sound pressure over a frequency band containing a sufficient number of eigen frequencies appears to be equivalent to averaging over source and receiver positions as well [see ref. 4].
- (4) There exist no truly "optimum" room dimensions for a reverberation room [see ref. 6].

The purpose of the research for the present paper was to determine the acoustic properties of the hard-walled acoustic facilities at NASA Langley Research Center to insure that the facilities meet the necessary requirements for the implementation of power flow techniques.

THEORY AND INSTRUMENTATION FOR THE SOUND-FIELD DIFFUSIVITY TESTS

A simple test for sound field diffusion was needed to test the quality of the sound-field of the various hard-walled acoustic facilities at NASA's LaRC. These acoustic facilities have irregular geometries making it difficult to calculate the eigen functions and natural frequencies of the rooms.

Consequently, an analytical study for determining room character was impractical. Although the literature¹⁻⁹ provided useful information on the character of reverberation chambers, only one paper⁸ presented a simple test for determining the sound-field diffusion in a room.

Cook, et al⁸ presents a simple experimental technique using two microphones for determining the sound-field diffusion in a room regardless of the room geometry. In this paper⁸ it is shown that in a three-dimensional acoustically diffuse field, the cross-correlation coefficient between two microphones separated by a distance r is given by

$$\rho_{12}(0) = \sin(kr)/kr, \quad (7)$$

where $\rho_{12}(0)$ is the cross-correlation coefficient (evaluated with zero time delay) and k is the wave number given by

$$k = \frac{2\pi f}{c_0}, \quad (8)$$

where f is frequency and c_0 is the speed of sound. Cook⁸ also shows that for a two-dimensional diffuse field in which the acoustic intensity vector is confined to two dimensions, the cross-correlation coefficient between two microphones separated by a distance r is given by

$$\rho_{12}(0) = J_0(kr) \quad (9)$$

where $\rho_{12}(0)$ and k are defined by equation (7) and J_0 is the 0th order Bessel function of the first kind. The theory can be extended to show that in a one-dimensional acoustic field (e.g. the field in an infinitely long tube) the cross-correlation coefficient between two microphones spaced at a distance r will be

$$\rho_{12}(0) = \cos(kr) \quad (10)$$

The cross-correlation coefficients are defined by the equation [see ref.11]

$$\rho_{12}(\tau) = \frac{R_{12}(\tau)}{\sqrt{R_{11}(\tau)R_{22}(\tau)}} \quad (11)$$

where the subscripts 1 and 2 denote the two microphones and τ represents the time delay. Mathematically the auto- and cross-correlation functions are given respectively by

$$R_{xx}(\tau) = \int_{-\infty}^{\infty} x(t) x(t+\tau) dt \text{ and,} \quad (12)$$

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} x(t+\tau) y(t) dt \quad (13)$$

The cross correlation coefficient, $\rho_{12}(0)$ can be calculated using the auto- and cross-power spectral density functions [see ref. 11]. The auto- and cross-spectral density functions are given respectively by

$$G_{xx}(f) = 2T[X(f) \cdot X^*(f)] \text{ and,} \quad (14)$$

$$G_{xy}(f) = 2T[X(f) \cdot Y^*(f)] , \quad (15)$$

where T is the length of the time record and $X(f)$, $Y(f)$ are the complex finite Fourier transforms of the two signals given by

$$X(f) = \frac{1}{T} \int_0^T x(t) e^{i\omega t} dt \quad (16)$$

$$Y(f) = \frac{1}{T} \int_0^T y(t) e^{i\omega t} dt \quad (17)$$

where the asterisk (*) denotes the complex conjugate. With this information the cross-correlation coefficient between microphones 1 and 2 may be calculated using the equation

$$\rho_{12}(0) = \frac{\int \text{Re}[G_{12}(f)] df}{\sqrt{\int G_{11}(f) df \cdot \int G_{22}(f) df}} \quad (18)$$

where $\text{Re}[\cdot]$ denotes the real part of a complex function and the limits of integration depend on the maximum frequency of interest.

For the experimental data in this paper, this method for calculating $\rho_{12}(0)$ was used. Since it is desirable to calculate $\rho_{12}(0)$ as a function of kr (i.e. as a function of frequency f) equation (18) must be modified slightly to

$$\rho_{12}(\tau=0;f) = \frac{\text{Re}[G_{12}(f)]}{\sqrt{G_{11}(f) \cdot G_{22}(f)}} \quad (19)$$

The equipment used for the tests is shown in the block diagram of figure 1. Two microphones were placed in the room under test at a fixed distance apart, .3048 m (1 ft.), with their diaphragms in the same plane. Independently generated white noise signals drove each of the 2 (or sometimes 4) speakers in the room. One-third octave band equalizers were used to condition the input signals to the speakers to ensure that the noise field in the room was uniform broadband noise. The speakers were placed close to the corners of the room in an effort to excite as many of the room modes as possible. A dual channel Fast Fourier analyzer obtained the cross- and auto-spectral densities from the microphone signals over a 0-2000 Hz frequency range with a 5 Hz bandwidth. A desktop calculator computed $\rho_{12}(0)$ as a function of frequency and plotted the results along with the theoretical curves.

The experiment was performed with three microphone orientations. In each case, the microphone diaphragms were parallel to one of the three orthogonal

coordinate axis directions defined by the intersecting floor and walls of the room. The Fast Fourier analyzer took 400 ensemble averages for each measurement. This ensured that the random portion of the sampling error was no more than ± 5 percent (see ref. 11).

Since instrumentation phase mis-match can detract from the accuracy of the measurements, the phase shift properties of the microphone-amplifier systems were carefully investigated prior to the experiments. The relative phase-match of the two channels due to the instrumentation is shown in figure 2. The phase-shift is seen to be no more than 4° at 5000 Hz.

REVERBERATION CHAMBER

A series of sound-field diffusivity tests using cross-correlation coefficients were performed on the ANRL reverberation chamber (Bldg. 1208). Total volume and surface area of the chamber are 220 m^3 (7769 ft^3) and 229 m^2 (2465 ft^2) respectively. The floor of the chamber is smooth concrete and the ceiling and walls are segmented sections (splayed walls) of concrete.

Prior to the sound-field diffusivity tests, two other properties of chamber were investigated. Assuming the chamber is a rectangular hard-walled enclosure, the first few eigen frequencies and the modal density as a function of frequency were calculated. The results of these calculations are given in table 1 and figure 3. The reverberation times of the chamber were measured in an earlier study¹⁰. The results of the measured reverberation times of the chamber are shown in figure 4.

Diffusivity tests on the reverberation chamber were performed using the equipment shown in figure 1. Four independently driven speakers positioned in

each of the four corners of the chamber were used to produce the uniform broadband noise field in the chamber. The microphones were placed 1.5 meters above the floor of the chamber in approximately the center of the working space of the room. The results of the cross-correlation measurements for the reverberation chamber are shown in figures 5 and 6. The narrowband (5 Hz bandwidth) cross-correlation coefficient measured over a 0-2000 Hz frequency range (0 to 12 kr range) is plotted in figure 5 for one of three different microphone orientations. The theoretical curves in figure 5 are the three dotted lines (calculated using equations (7), (9), and (10)) and the solid curve is the measurement data. It is evident from this figure that the mean value of the measurement data regresses to the theoretical curve for a diffuse acoustic field in three dimensions ($\sin[kr]/kr$). The standard deviation of the data about the theoretical curve, σ , is .1366. Morrow⁹ postulates that in order to obtain good agreement with Cook's theory it is necessary to average the data over a frequency band containing many room modes. If this condition is not satisfied large variations from the theoretical curves may be expected. A 50 Hz band moving average was performed on the data of figure 5. The result of this moving average is plotted in figure 6 along with the theoretical curve for a diffuse acoustic field in three dimensions ($\sin[kr]/kr$). Much better agreement with the theory is obtained by using this band average technique ($\sigma=.0649$). Figure 6 indicates that the acoustic field in the reverberation chamber is acceptable for sound power measurements over the 100-2000 Hz frequency range. Similar results were obtained for the measurements with the other two microphone orientations.

TRANSMISSION LOSS FACILITY

The ANRL transmission loss facility is a two-room acoustic test facility designed for noise reduction (NR) and transmission loss (TL) measurements on light aircraft panels. It consists of two chambers, a source room and a receiving room, with an adjoining wall. The source room is used to create an incident sound field on the aircraft panel under test. The second chamber, called the receiving room, is used to measure the noise transmitted through the aircraft panel. The aircraft panel itself is positioned in a 1.23 m by 1.525 m section in the adjoining wall between the two rooms.

The source room of this facility measures 2.7 m x 2.9 m x 3.9 m (9' x 9.5' x 12.75'). Total volume and surface area of the room are 30.9 m³ (1090 ft³) and 59.7 m² (645 ft²) respectively. The room has a tile floor, plaster board walls and a suspended acoustic tile ceiling. Assuming the room is a rectangular hardwalled enclosure, the first few eigen frequencies and the modal density as a function of frequency were calculated. These calculations are given in table 2 and figure 7. Measured and calculated octave band reverberation times are shown in figure 8.

Reverberation time was calculated using the Millington-Sette¹² equation given by

$$T_{60} = \frac{.049V}{\sum S_i \ln(1-\alpha_i)} \quad (20)$$

where T_{60} is reverberation time, $V(\text{ft}^3)$ is the room volume, $S_i(\text{ft}^2)$ is surface area of the i^{th} surface in the room, and α_i is the acoustic random incidence absorption coefficient of the i^{th} material in the room. The values of V and S_i were measured values and the α_i values were obtained

from reference 13 and measurements. The values of α_i used in the calculations are given in table 3.

Measurements of reverberation time were taken several times for each octave band at a single location in the room using a commercially available reverberation time meter. The results of the measurements were averaged into a single reverberation time for each octave band and the results plotted in figure 8. This figure shows that the measured and predicted values of the reverberation time agree in the lower frequency bands only when the airspace above the suspended ceiling is taken into consideration in the calculations. This indicates that below 1 kHz, the airspace above the ceiling has a significant effect on the reverberation time of the room.

Diffusivity tests on the source room were performed using the equipment shown in figure 1. Two independently driven speakers, positioned in corners of the room, opposite the aircraft panel, were used to produce the uniform broadband noise field in the chamber. The microphones were placed 1.5 meters above the floor of the room in approximately the center of the working space of the room. An all aluminum aircraft panel with stringers and frames separated the source room and receiving room for the duration of the diffusivity tests. An example of the results of the cross correlation measurements are shown in figures 9 and 10. The narrowband (5 Hz bandwidth) cross correlation coefficient measured over a 0-2000 Hz frequency range is plotted against the theoretical curves in figure 9 for one of three different microphone orientations. The measurement data of figure 9 exhibit a significant amount of scatter about the theoretical curve for a three dimensional diffuse field ($\sin[kr]/kr$). The standard deviation of the data about the theoretical curve, σ , is .2954. A 50 Hz moving band average of the measurement data was performed and is shown in figure 10. This figure shows that the data deviates

considerably from the theoretical curve ($\sigma=.1529$). Comparison of figure 10 (source room) with figure 6 (reverberation chamber) indicates that the quality of the sound field in the reverberation chamber is superior to that of the source room of the transmission loss facility as expected.

In an effort to improve the quality of diffuseness in the source room, the suspended acoustical tile ceiling was removed. This increased the height of the room by 1 meter so that the total volume and surface area of the room are 41.9 m^3 and 72.9 m^2 respectively. The ceiling of the room, without the acoustic tile, consists of irregularly shaped steel reinforced concrete.

Reverberation time was measured, as before, with the source room in its new configuration. These data were compared with the previously measured reverberation times. The comparison is shown in figure 11. This figure shows that the reverberation time of the source room was increased substantially as expected by removing the acoustical tile ceiling.

Cross-correlation diffusivity tests were performed on the source room with its new ceiling configuration using the same techniques discussed previously. The results are shown in figures 12 and 13. The standard deviation of the narrowband measurement data about the theoretical curve ($\sin[kr]/kr$) in figure 12 is $\sigma=.2969$. Comparison of figures 10 and 13 indicates that the diffuseness of the source room was improved substantially by removing the acoustical tile ceiling ($\sigma=.1277$). The enhanced quality of the sound field in the room is particularly evident in the frequency range of 500-1500 Hz (3 to 9 kr).

The receiving room of the ANRL transmission loss facility measures $4.06 \text{ m} \times 2.9 \text{ m} \times 2.74 \text{ m}$ ($13\text{-}1/3' \times 9\text{-}1/2' \times 9'$). Total volume and surface area of the room are 32.3 m^3 (1140 ft^3) and 61.7 m^2 (664 ft^2) respectively. The room has a tile floor, plasterboard walls and a rigid-backed acoustic tile ceiling.

The receiving room is dynamically isolated from the building which houses the facility and has double concrete walls with a double door. Measurements of flanking transmission loss (for sound entering the receiving room via paths other than the panel) indicate that the receiving room may be used to measure sound levels that are 80 dB lower than the sound levels in the source room. The ambient noise level of the receiving space is less than 20 dB which is generally below the noise floor of the condenser microphones used for measurements.

Assuming that the receiving room is a rectangular hardwalled enclosure, the first few eigen-frequencies and the modal density as a function of frequency were calculated. These calculations are given in table 4 and figure 14. Measured and calculated octave band reverberation times are shown in figure 15.

For many applications, such as the measurement of transmission loss, it may be desired that the receiving room have a very high absorptivity. If transmission loss is being measured by an array of microphones in the receiving space or an acoustic intensity meter (see ref. 14), it is necessary to increase the acoustic absorption in the receiving room to a level which approaches the absorption of an anechoic space. An attempt was made to increase the absorption of the receiving room by placing six 1.2 m x 2.5 m x .10 m thick fiberglass panels in the room. The fiberglass panels were placed parallel to the wall adjoining the source and receiving rooms and were evenly spaced 60 cm apart. Reverberation times in octave bands were measured, as before, with the receiving room in this new configuration. A comparison of the results is shown in figure 16. This figure demonstrates that the absorption in the receiving space can be increased dramatically by the inclusion of relatively few fiberglass panels.

CONCLUSIONS

The results of this indicate that it is possible to create a diffuse sound field in the ANRL reverberation chamber over a 100-2000 Hz frequency range. These results were for a specific system (viz, four independently driven speakers in each corner of the chamber) and data were taken only near the center of the room. It is possible that the quality of the sound field in this frequency range as well as higher frequencies will differ markedly depending on the system used to drive the sound field and on the location of the source and receiver in the chamber.

The quality of the sound field in the source room of the transmission loss facility is acceptable for measurement of transmission loss over a 200-2000 Hz frequency range when using two independently driven speakers to produce the incident sound field. Random incidence transmission loss measurements in the frequency range below 200 Hz would be suspect due to the low modal density of the source room in this frequency range.

The absorption of the receiving room of the transmission loss facility can be increased considerably by incorporating fiberglass panels.

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TABLE 1

REVERBERATION CHAMBER
CALCULATED EIGEN FREQUENCIES

| <u>MODE NUMBERS</u> | | | <u>FREQUENCY, Hz</u> |
|----------------------|----------------------|----------------------|----------------------|
| <u>M_x</u> | <u>M_y</u> | <u>M_z</u> | |
| 1 | 0 | 0 | 21.6 |
| 0 | 1 | 0 | 28.1 |
| 1 | 1 | 0 | 35.5 |
| 0 | 0 | 1 | 40.2 |
| 2 | 0 | 0 | 43.3 |
| 1 | 0 | 1 | 45.7 |
| 0 | 1 | 1 | 49.1 |
| 2 | 1 | 0 | 51.6 |
| 1 | 1 | 1 | 53.6 |
| 0 | 2 | 0 | 56.3 |

TABLE 2

TRANSMISSION LOSS FACILITY - SOURCE ROOM

CALCULATED EIGEN FREQUENCIES

| <u>MODE NUMBERS</u> | | | <u>FREQUENCY, Hz</u> |
|----------------------|----------------------|----------------------|----------------------|
| <u>M_x</u> | <u>M_y</u> | <u>M_z</u> | |
| 1 | 0 | 0 | 44.13 |
| 0 | 1 | 0 | 59.23 |
| 0 | 0 | 1 | 62.52 |
| 1 | 1 | 0 | 73.86 |
| 1 | 0 | 1 | 76.52 |
| 0 | 1 | 1 | 86.12 |
| 2 | 0 | 0 | 88.26 |
| 1 | 1 | 1 | 96.77 |
| 2 | 1 | 0 | 106.29 |
| 2 | 0 | 1 | 108.16 |

TABLE 3

ABSORPTION COEFFICIENTS, α

| MATERIAL | OCTAVE BAND CENTER FREQUENCY, Hz | | | | | |
|--|----------------------------------|------------|------------|-------------|-------------|-------------|
| | <u>125</u> | <u>250</u> | <u>500</u> | <u>1000</u> | <u>2000</u> | <u>4000</u> |
| PLASTER WALL | .013 | .015 | .02 | .03 | .04 | .05 |
| *ACOUSTIC CEILING TILE | .1 | .15 | .25 | .3 | .4 | .4 |
| †ACOUSTIC CEILING TILE W/ AIRSPACE ABOVE CEILING | .3 | .45 | .50 | .4 | .4 | .4 |
| GLASS | .35 | .25 | .18 | .12 | .07 | .04 |
| CONCRETE | .01 | .01 | .01 | .02 | .02 | .02 |

* Values for the acoustic ceiling were measured using the NASA Langley Research Center's impedance tube facility.

† Corrections for the airspace above the ceiling were taken from Fig 10.13 of reference [12].

TABLE 4

TRANSMISSION LOSS FACILITY - RECEIVING ROOM
CALCULATED EIGEN FREQUENCIES

| <u>MODE NUMBERS</u> | | | <u>FREQUENCY, Hz</u> |
|----------------------|----------------------|----------------------|----------------------|
| <u>M_x</u> | <u>M_y</u> | <u>M_z</u> | |
| 1 | 0 | 0 | 42.21 |
| 0 | 1 | 0 | 59.23 |
| 1 | 1 | 0 | 62.52 |
| 0 | 0 | 1 | 72.73 |
| 2 | 0 | 0 | 75.43 |
| 1 | 0 | 1 | 84.42 |
| 0 | 1 | 1 | 86.12 |
| 2 | 1 | 0 | 95.91 |
| 1 | 1 | 1 | 103.13 |
| 0 | 2 | 0 | 105.15 |

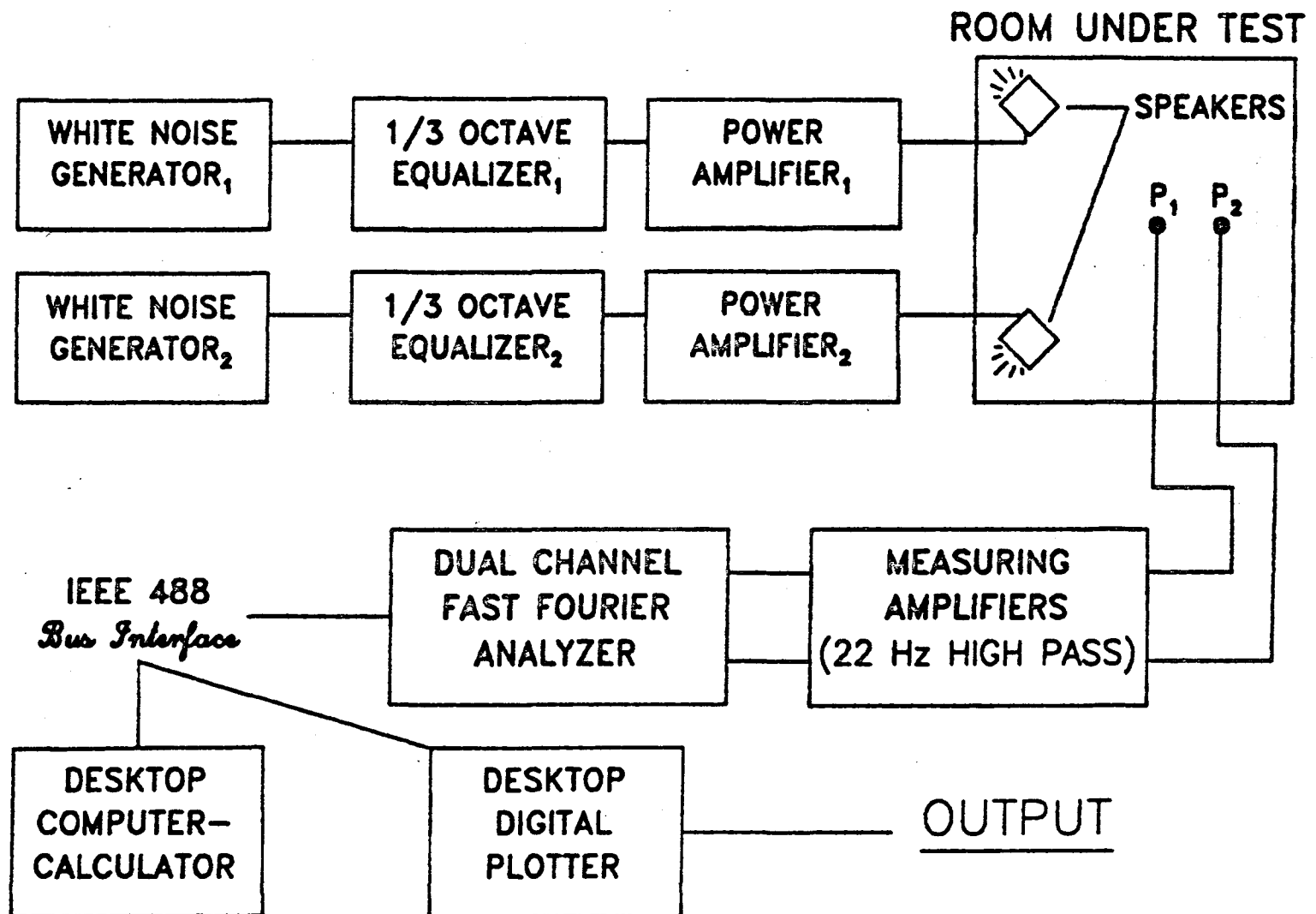


Figure 1.- Instrumentation block diagram for the diffusivity tests.

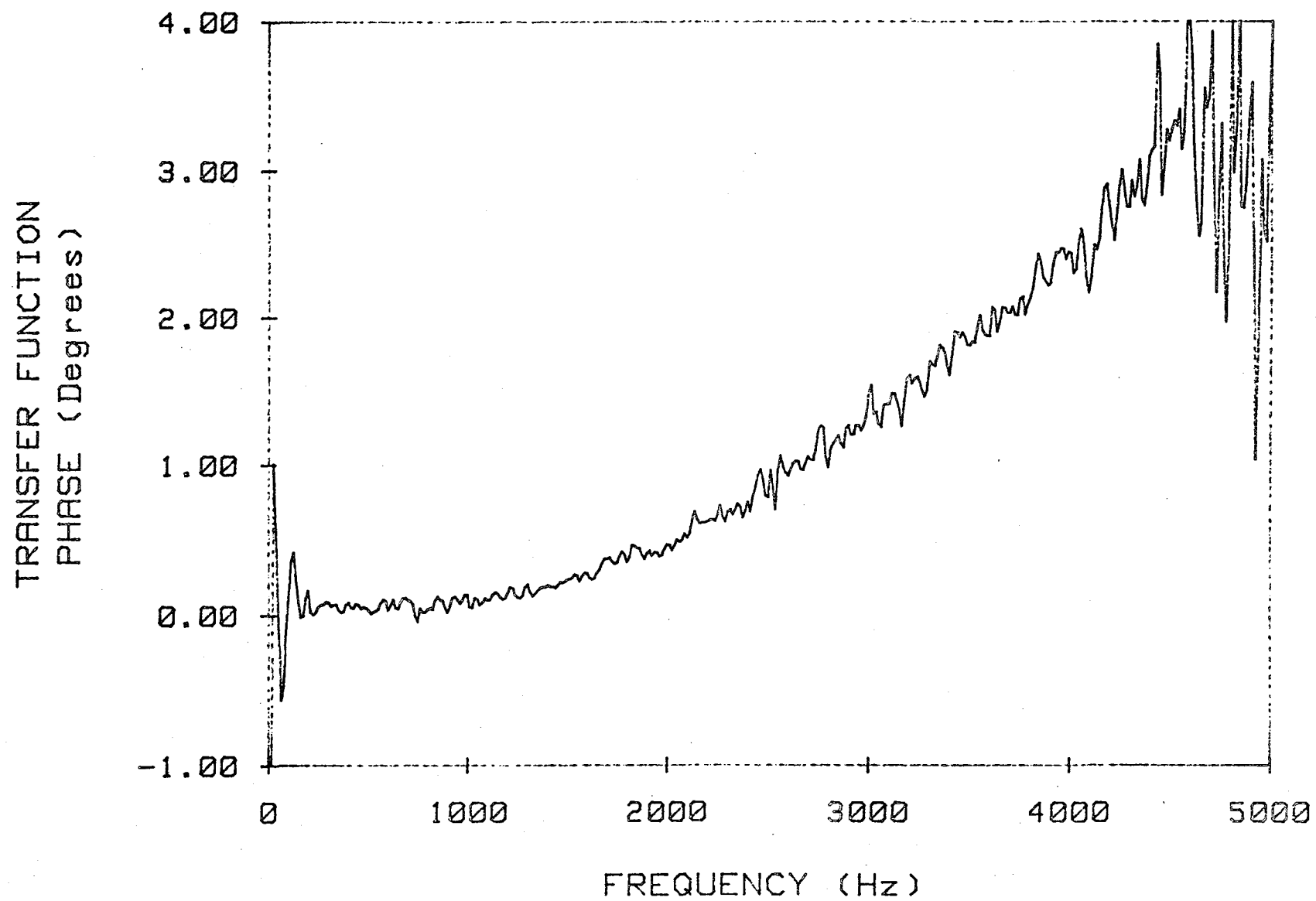


Figure 2.- Instrumentation phase mis-match for the measurement system.

REVERBERATION CHAMBER

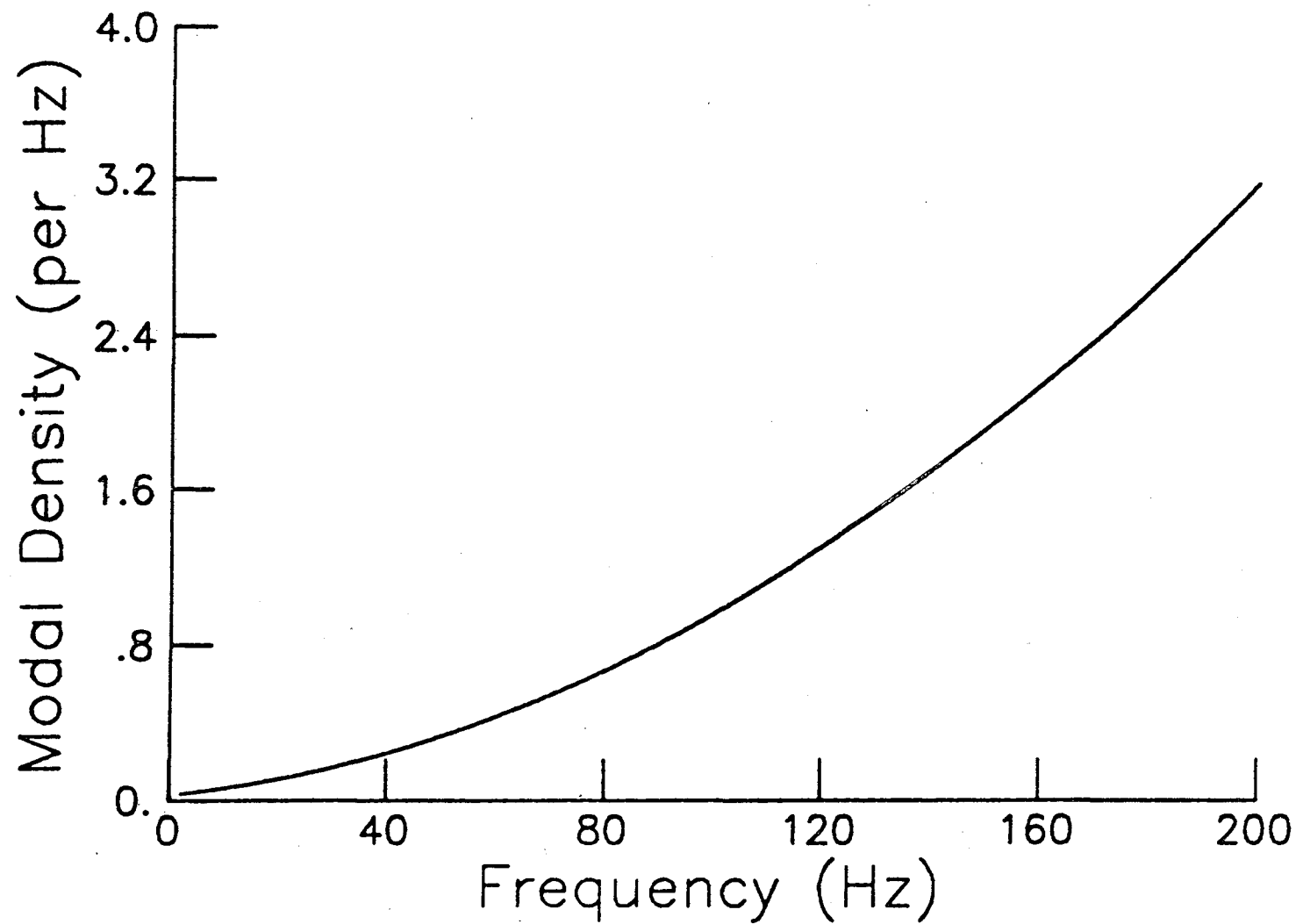


Figure 3.- Calculated modal density of the reverberation chamber.

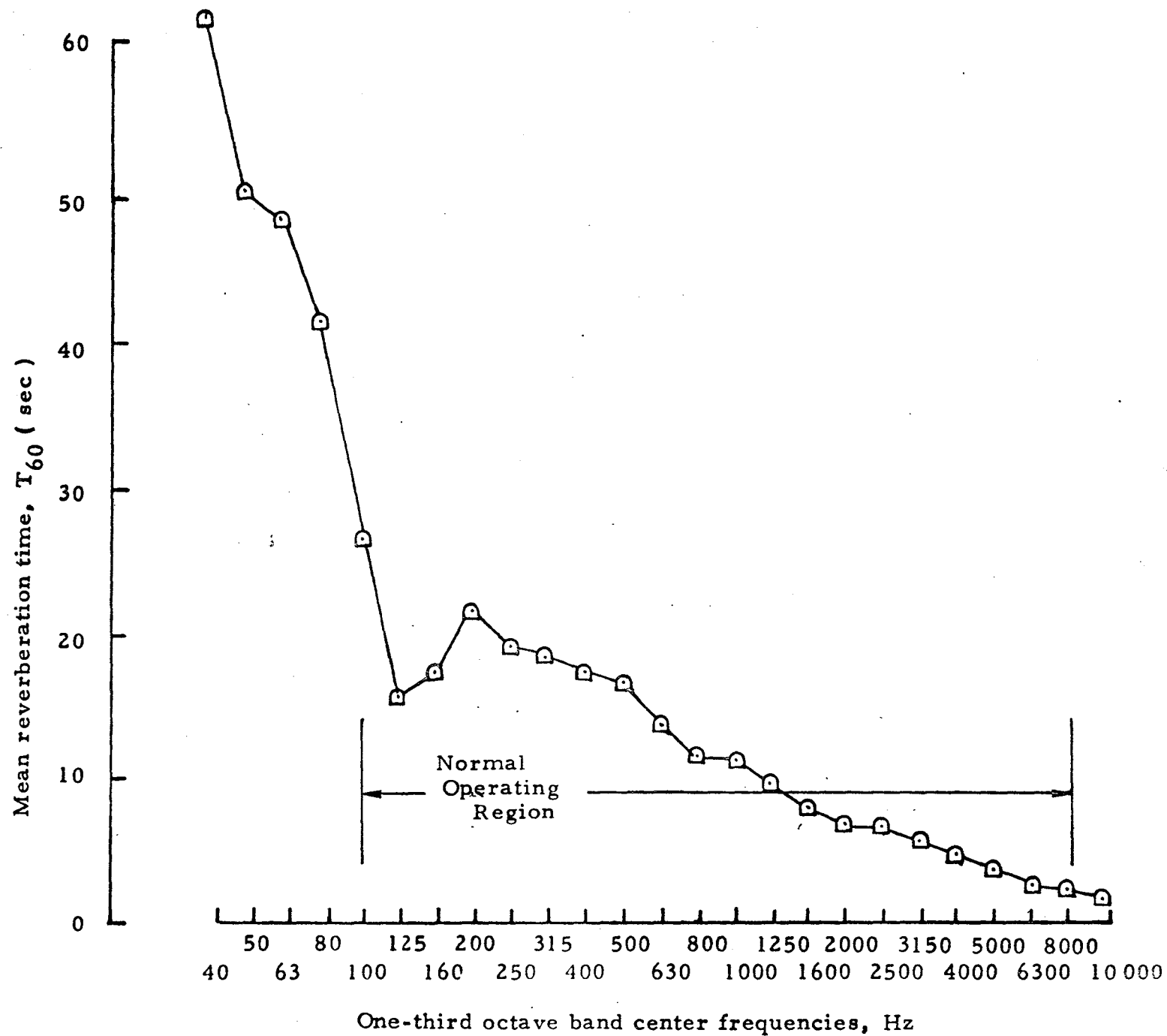


Figure 4.- Measured reverberation time in the reverberation chamber.

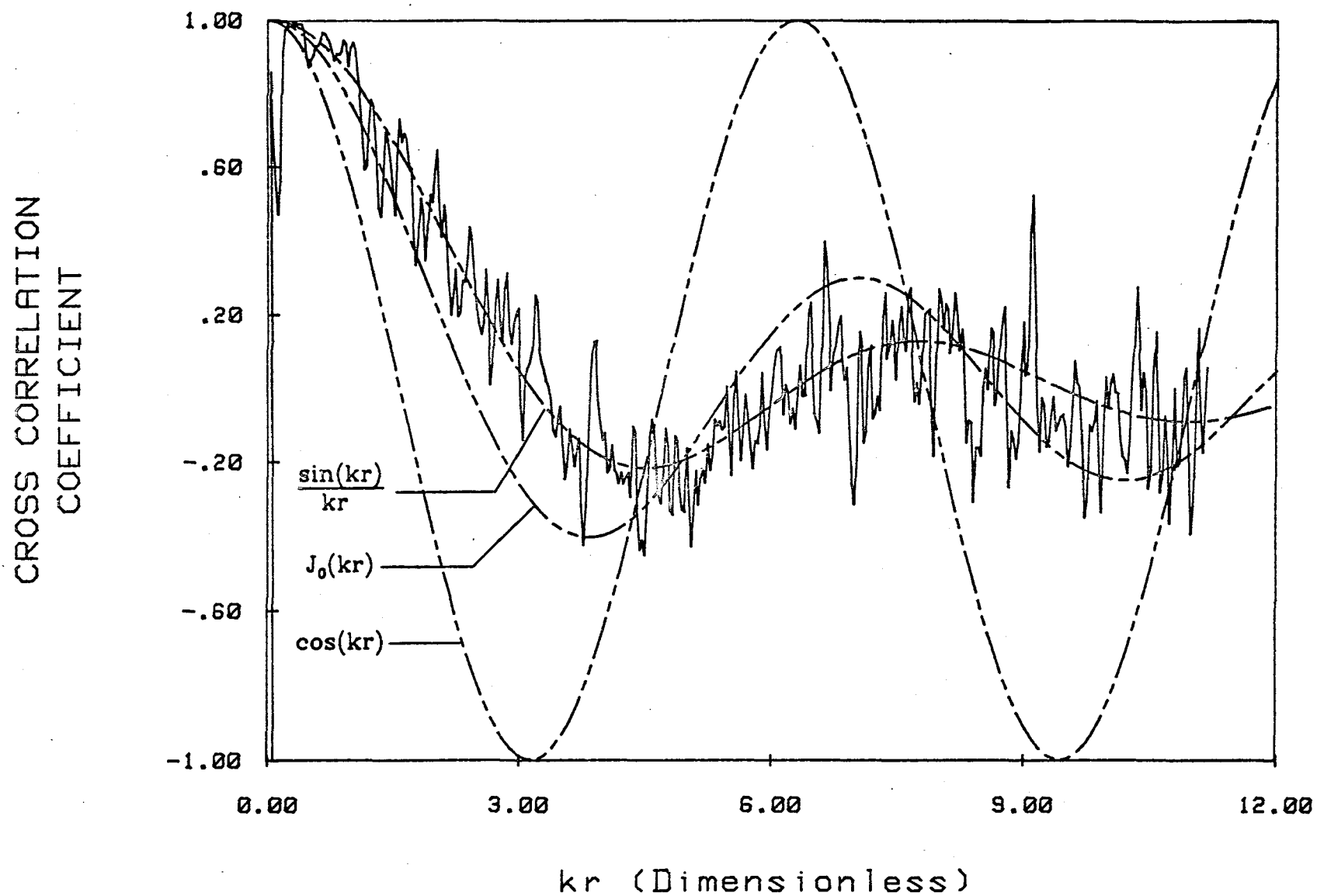


Figure 5.- Results of the cross correlation coefficient measurements of diffusivity in the reverberation chamber.

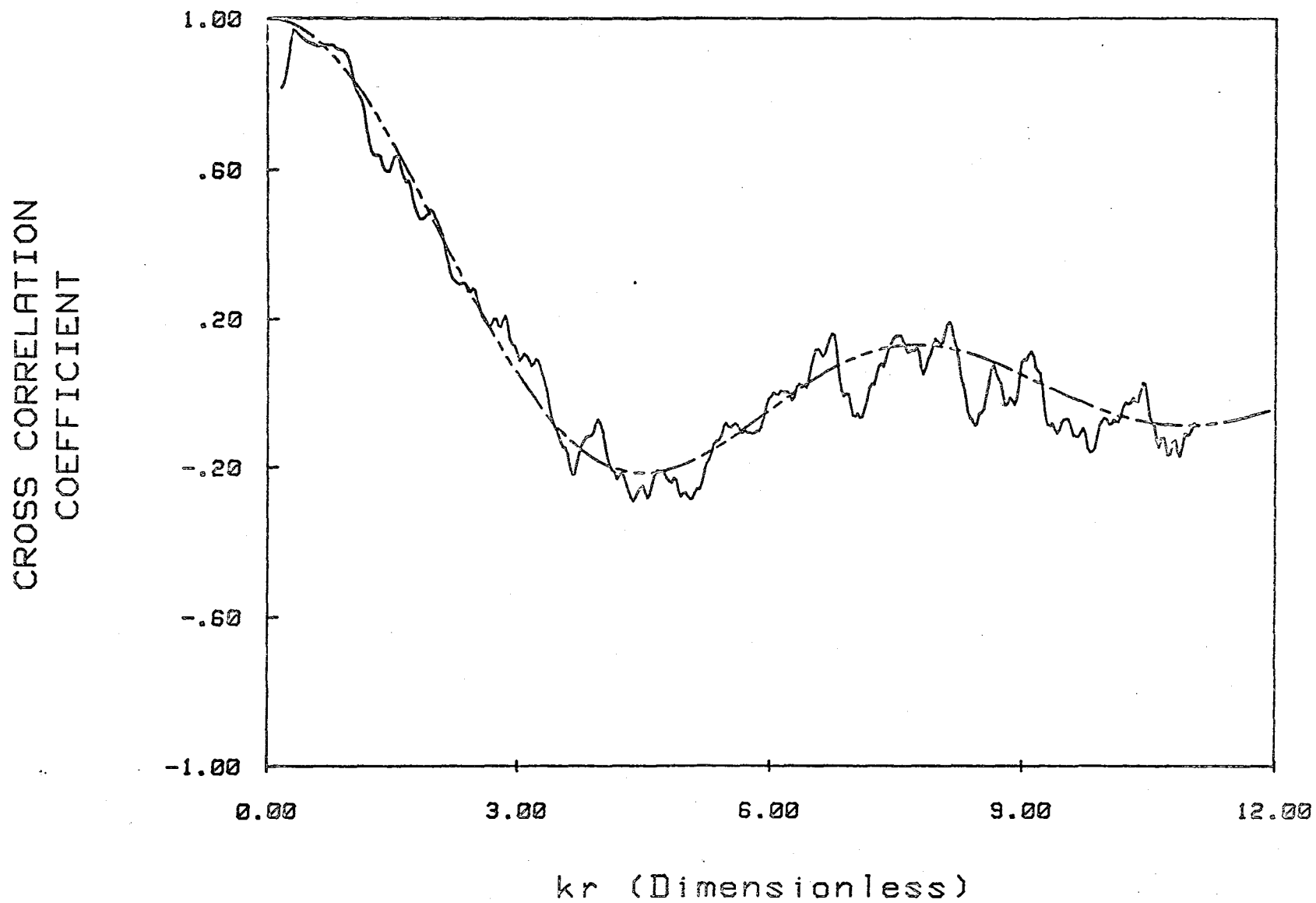


Figure 6.- Band averaged cross correlation coefficient measurements of diffusivity in the reverberation chamber.

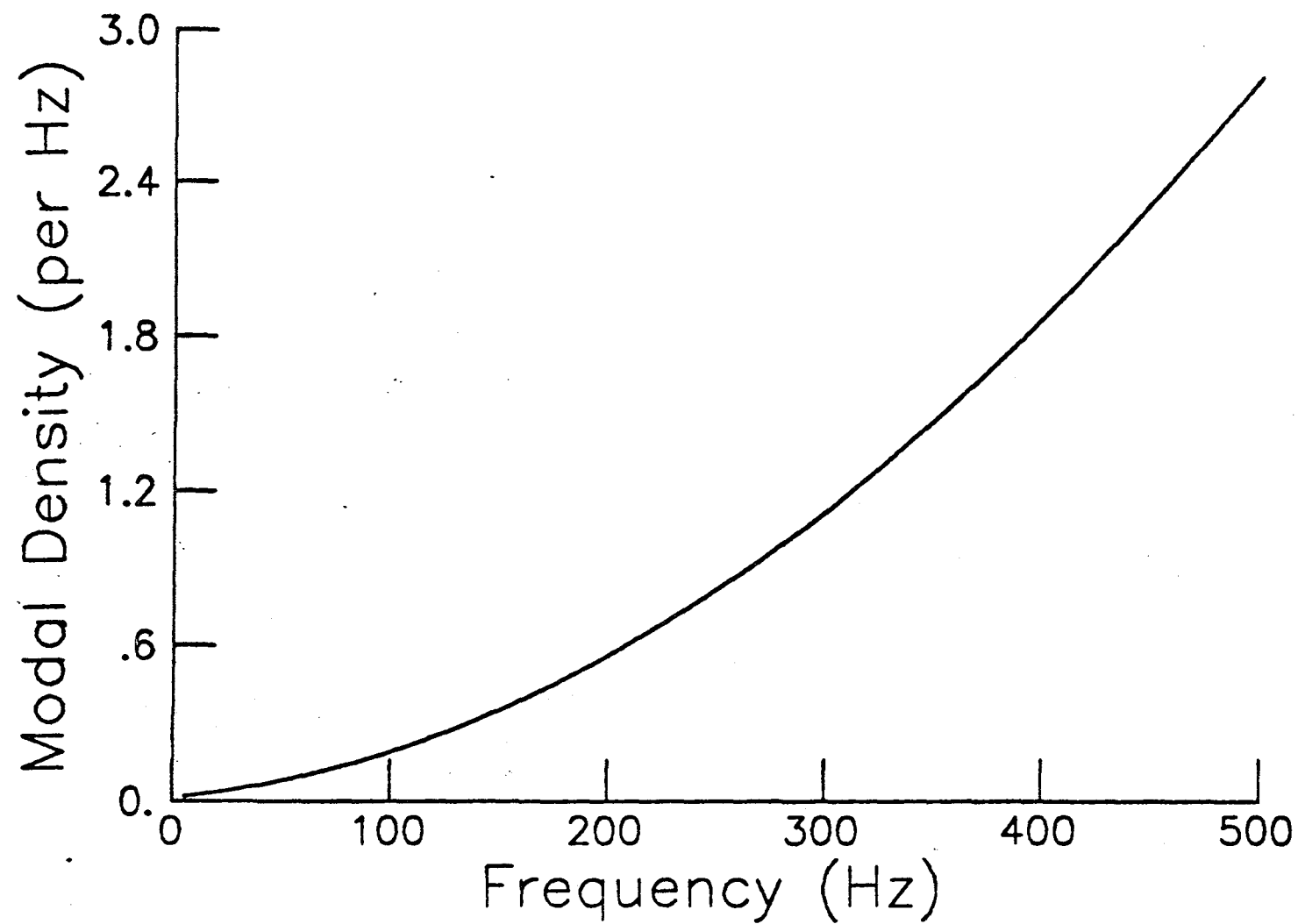


Figure 7.- Calculated modal density of the source room.

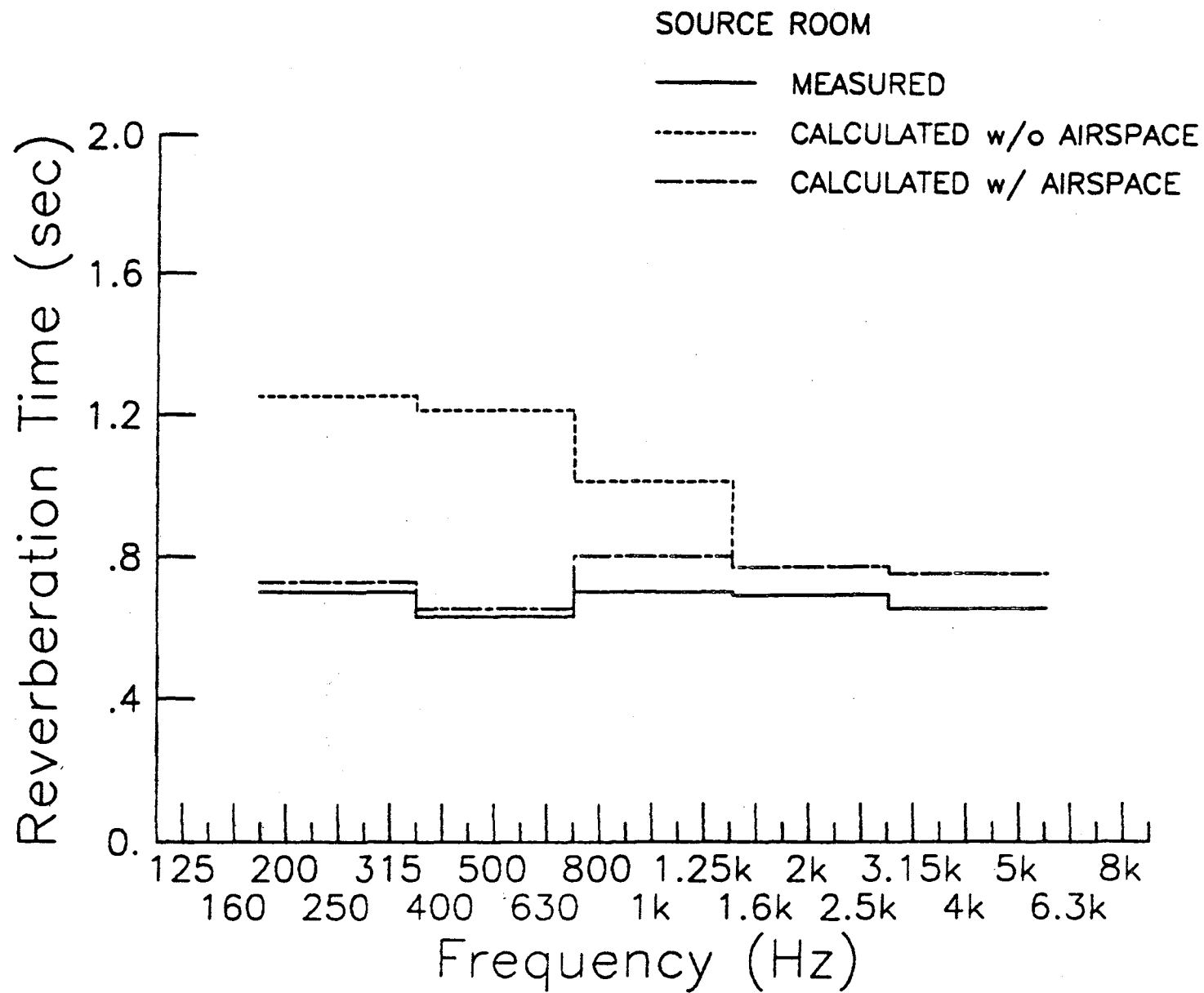


Figure 8.- Reverberation time in the source room.

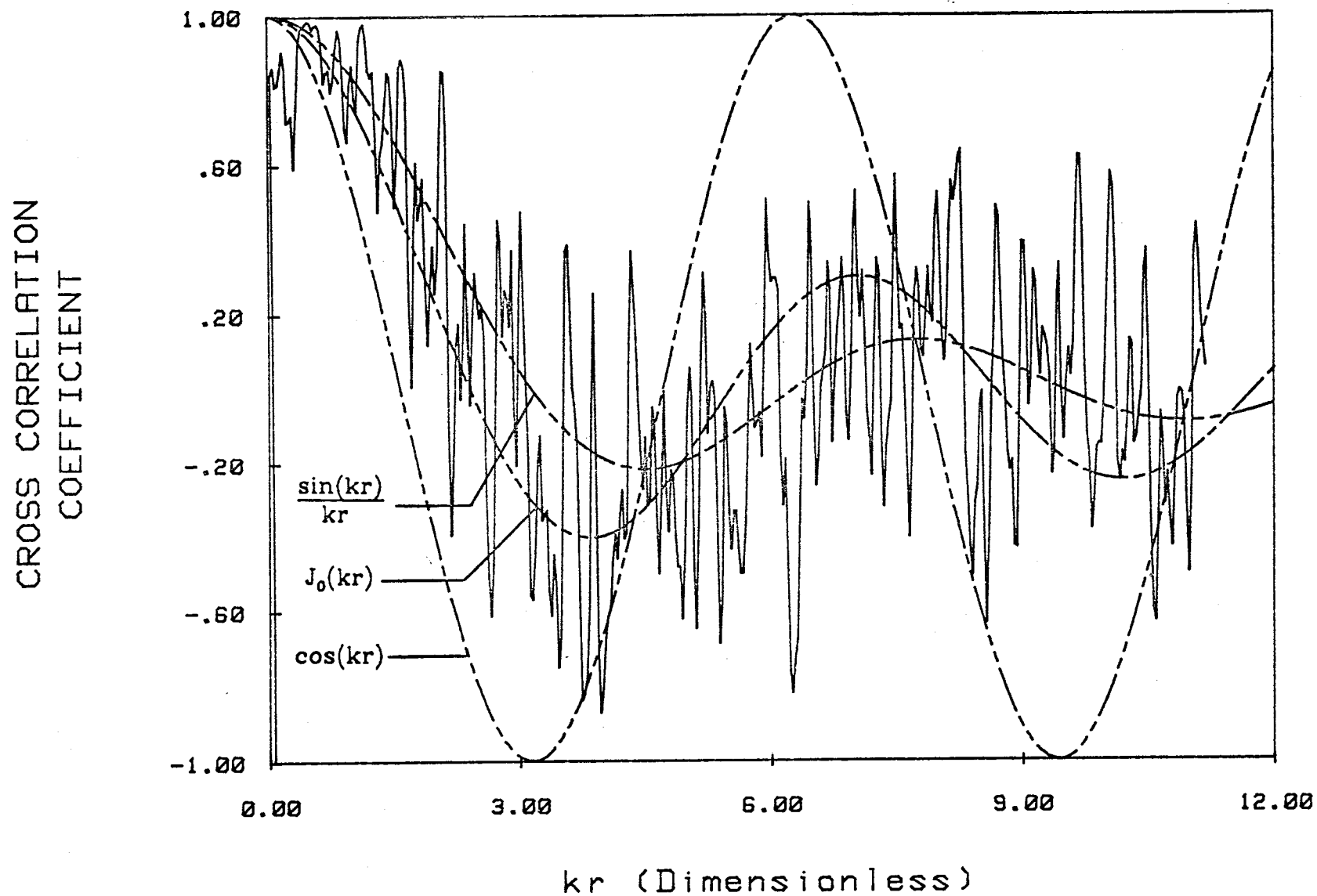


Figure 9.- Results of the cross correlation coefficient measurements of diffusivity in the source room.

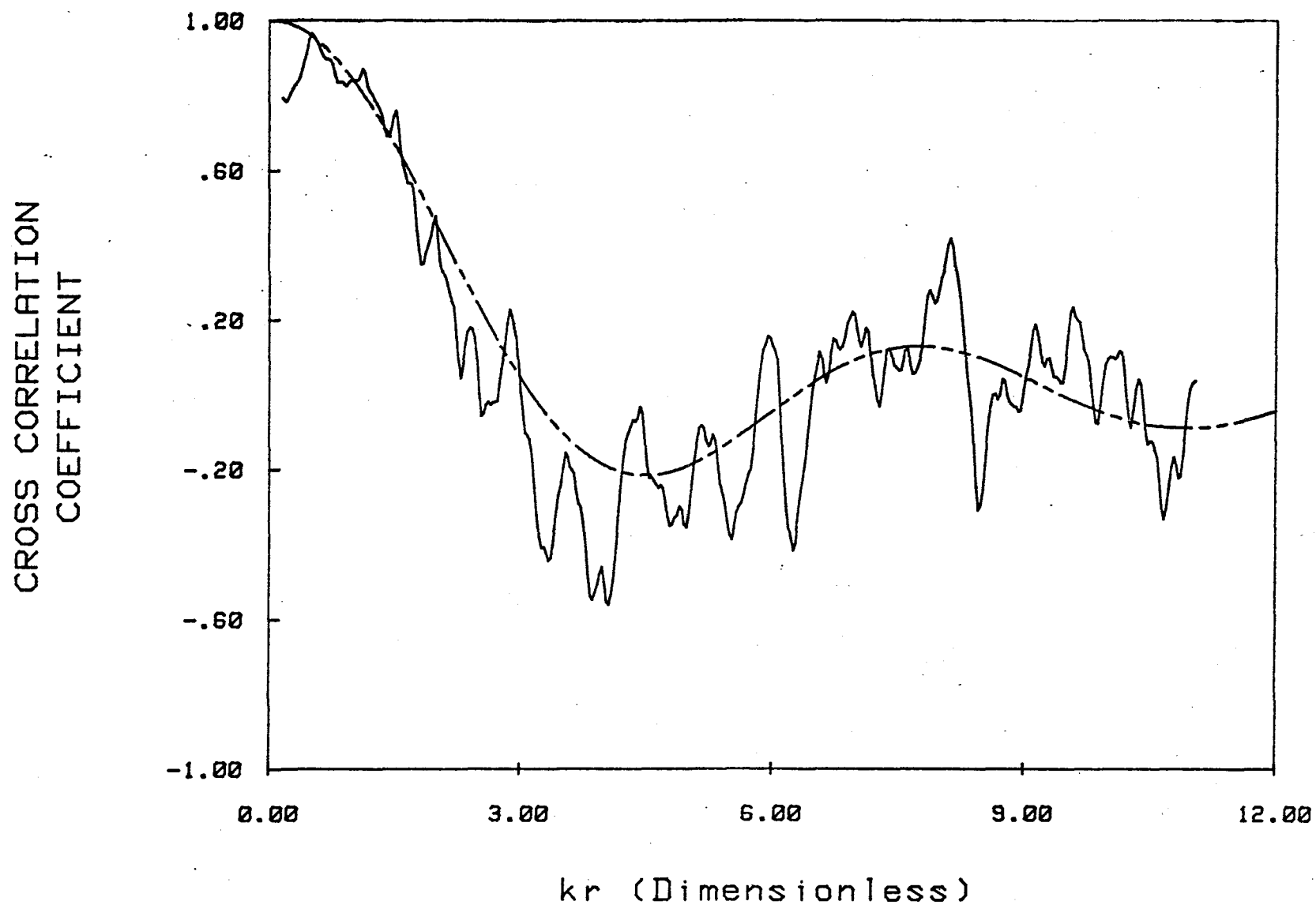


Figure 10.- Band averaged cross correlation coefficient measurements of diffusivity in the source room.

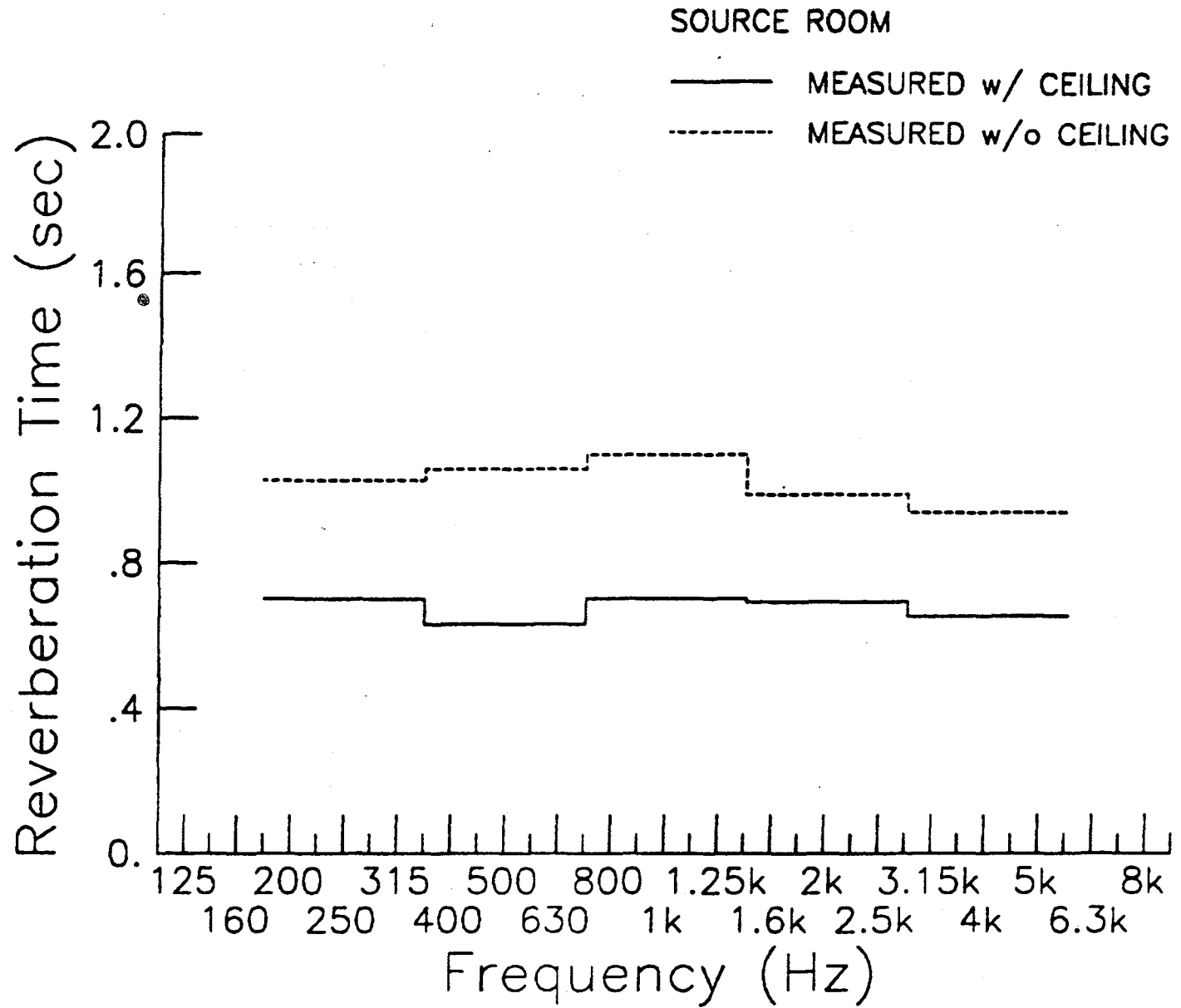


Figure 11.- Increase in reverberation time in the source room with the ceiling modifications.

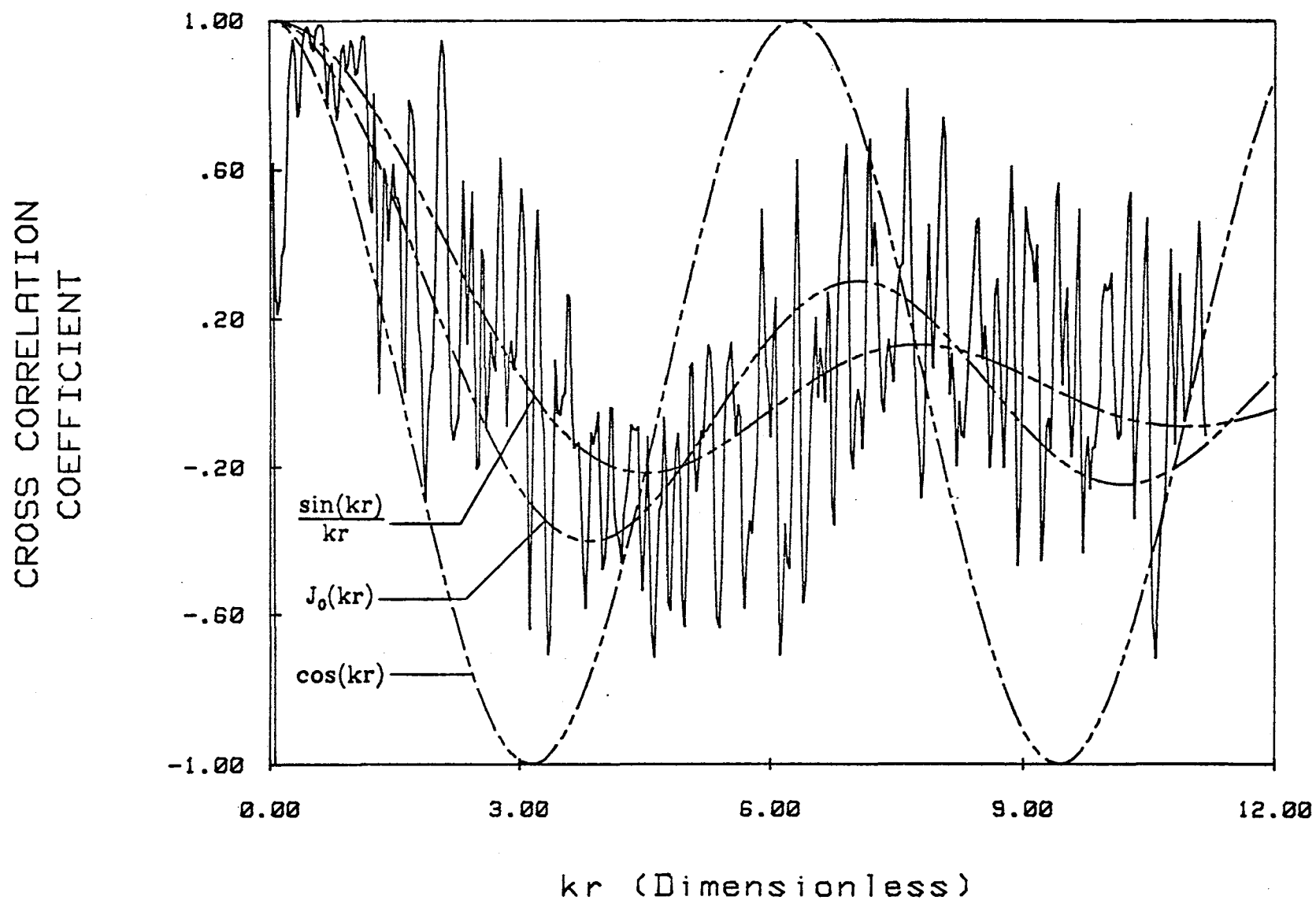


Figure 12.- Results of the cross correlation coefficient measurements in the source room with the ceiling modifications.

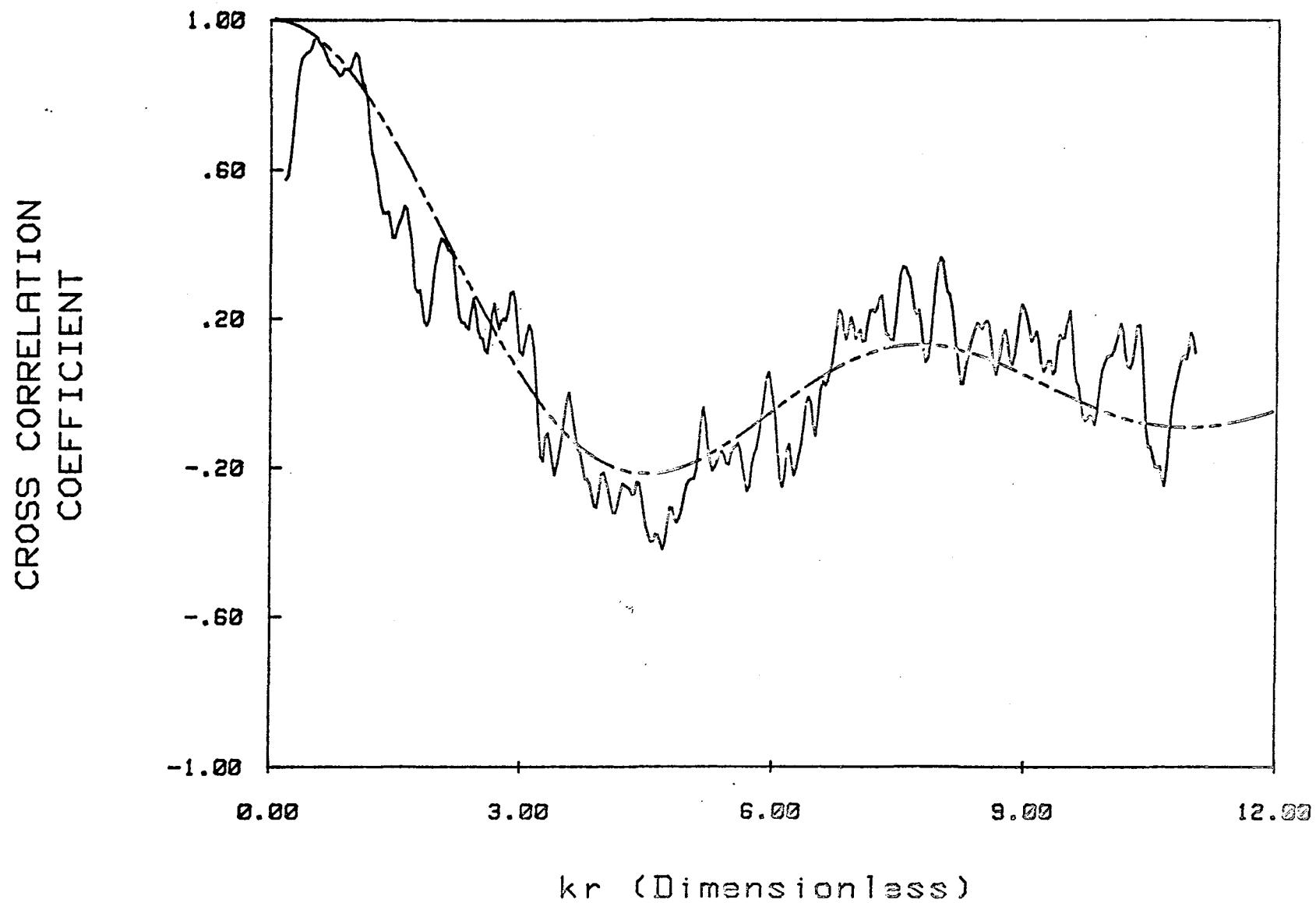


Figure 13.- Band averaged cross correlation coefficient measurements in the source room with the ceiling modifications.

RECEIVING ROOM

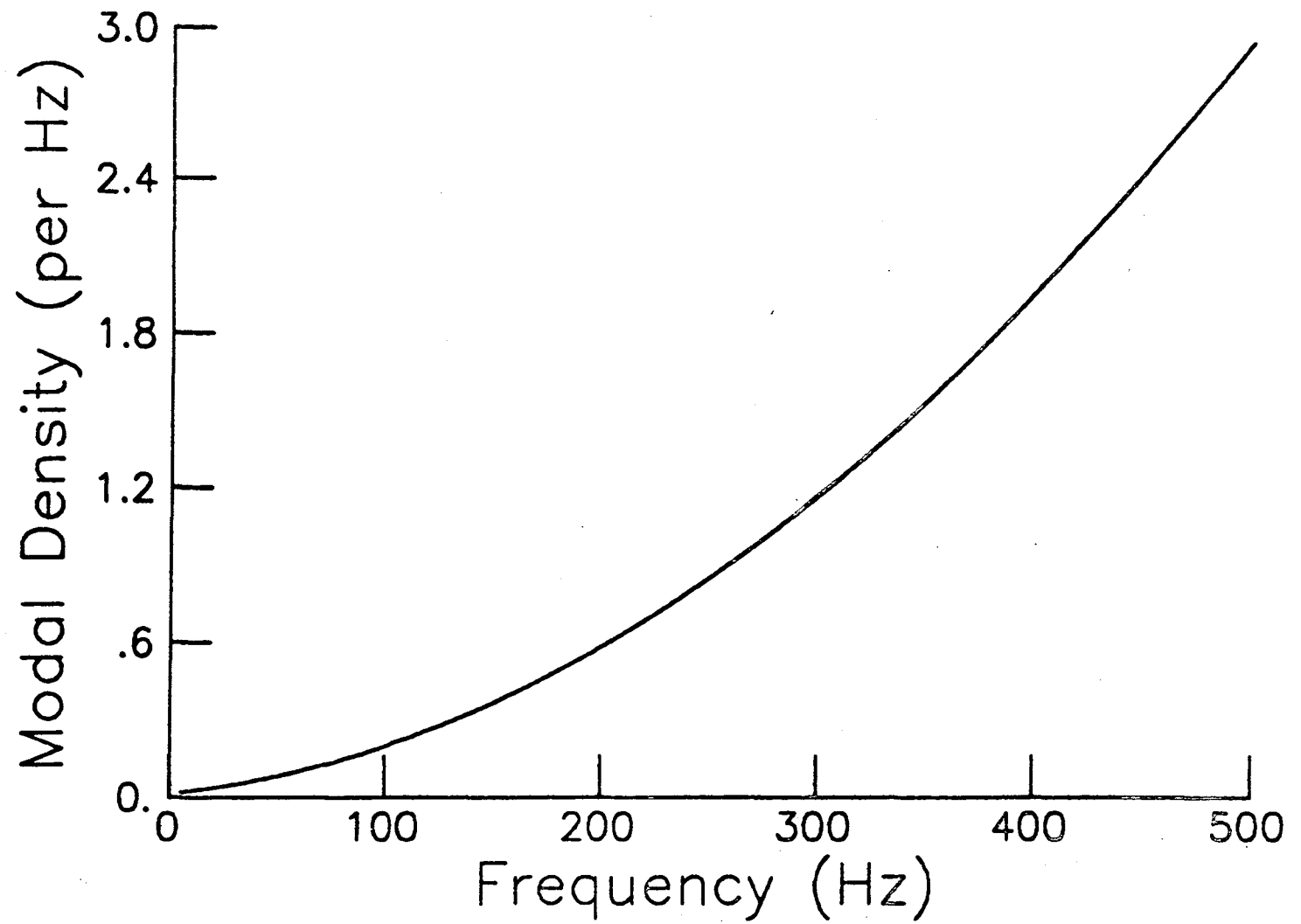


Figure 14.- Calculated modal density of the receiving room.

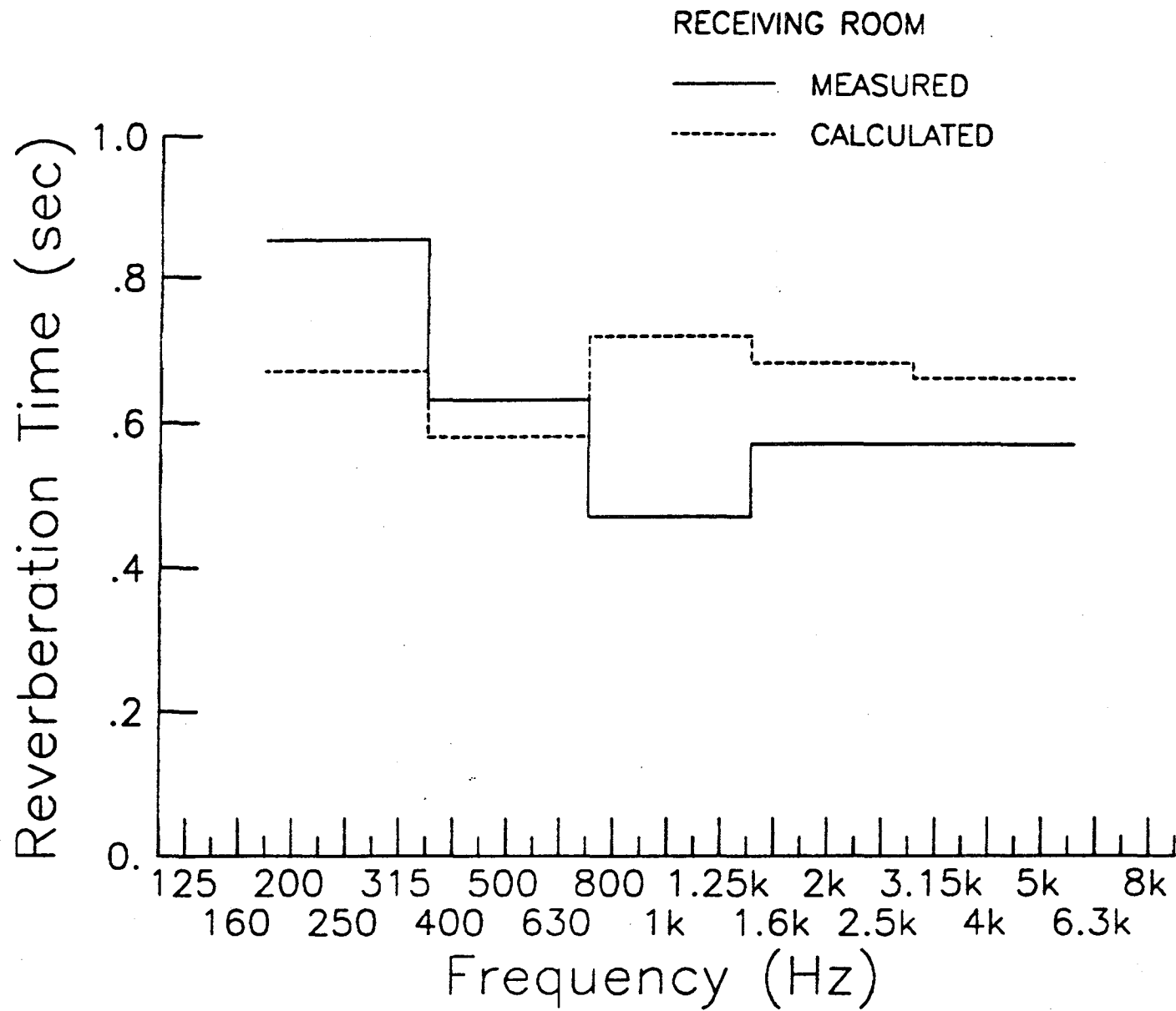


Figure 15.- Reverberation time in the receiving room.

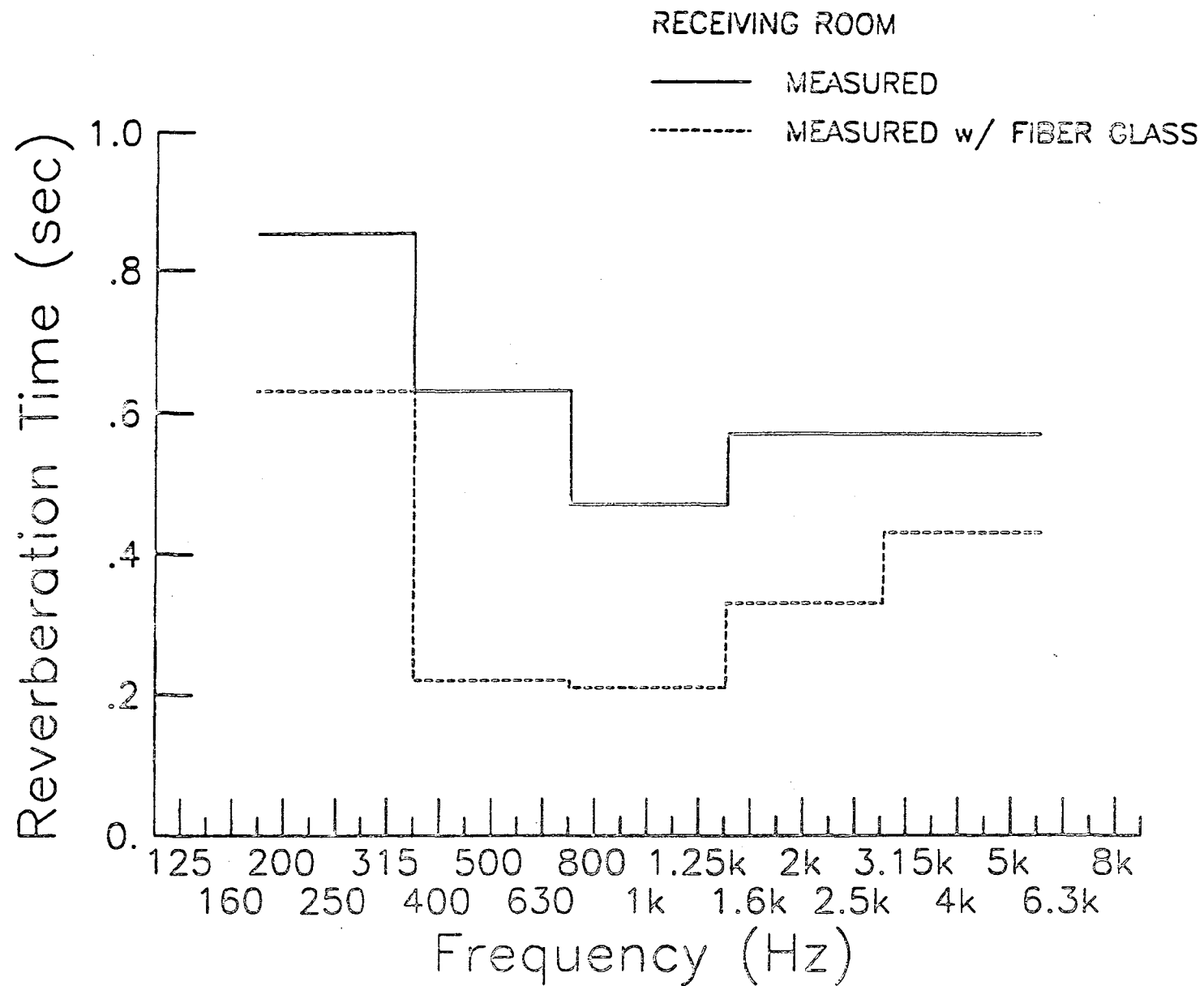


Figure 16.- Decrease in reverberation time in the receiving room with the addition of fiberglass panels.

| | | | | | |
|--|--|--|--|---|--|
| 1. Report No. NASA TM-83275 | | 2. Government Accession No. | | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle Sound Field Diffusivity in NASA Langley Research Center Hardwalled Acoustic Facilities | | | | 5. Report Date March 1982 | |
| | | | | 6. Performing Organization Code 2630 | |
| 7. Author(s) Michael C. McGary | | | | 8. Performing Organization Report No. 505-33-53-03 | |
| 9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665 | | | | 10. Work Unit No. | |
| | | | | 11. Contract or Grant No. | |
| 12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC | | | | 13. Type of Report and Period Covered Technical Memorandum | |
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| 15. Supplementary Notes | | | | | |
| 16. Abstract A study using cross-correlation measurements was performed to determine the quality of the sound fields in the ANRL reverberation room and the ANRL transmission loss facility. The results indicate the level of sound field diffuseness which may be attained in these hardwalled acoustic facilities. | | | | | |
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